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Using Normative Data and Unilateral Hopping Tests to Reduce Ambiguity in Return-to-Play Decisions

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Context: After a lower extremity injury, patients often return to sport (RTS) when the injured limb's performance on unilateral hopping tests is similar to that of the uninjured limb. However, the exact target symmetry value patients must reach before the RTS is unclear.

Objective: To identify variables that predict limb symmetry index (LSI) values on 6 unilateral hopping tests in healthy, physically active adults.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: In total, 275 healthy, physically active adults, consisting of recreational athletes (n = 198), National Collegiate Athletic Association Division I student-athletes (n = 56), and Army Reserve Officer Training Corps cadets (n = 21), volunteered to participate (143 men, 132 women, age = 20.16 ± 2.19 years, height = 172.66 ± 10.22 cm, weight = 72.64 ± 14.29 kg).

Intervention(s): Each participant completed 3 speed (6-m crossover-hop, side-hop, figure-8 hop) and 3 distance (triple–crossover-hop, lateral-hop, medial-hop) functional performance tests on both limbs.

Main Outcome Measure(s): Mean performance of the dominant and nondominant limbs and LSI values. Two multiple regression models were used to find variables that might help to predict a participant's LSI for each functional performance test.

Results: The models helped to predict limb symmetry for 10 of the 12 multiple regressions. Unilateral limb performance was the best predictor of LSI values, as it was statistically significant in 11 of the 12 regression models. Sex and body mass index were significant predictor variables for the side hop and figure-8 hop, respectively.

Conclusions: We found significant predictor variables that clinicians can use in the absence of baseline testing to determine patient-specific LSI values. Individualizing RTS decisions in this way may help to minimize subjectivity in the decision-making process and ensure a safe and timely return to competition.

Key Words: limb symmetry, functional performance, hop tests

Key Points

- On unilateral hopping tests, healthy, physically active adults demonstrated various limb symmetry values.
- Regression analyses identified variables that can help predict limb symmetry indexes.
- In the absence of baseline data, clinicians can use our regression equations to formulate patient-specific return-to-play benchmarks.

Return to play (RTP) is the decision-making process sports medicine professionals use to determine when athletes can return to full sport participation with minimal risk of injury to themselves and others.[1–7] Deciding whether an athlete may return to a competitive sport environment is an essential skill that all sports medicine professionals should possess. Not only does the future health and safety of the athlete depend on an accurate RTP decision, but potential legal ramifications exist for any clinician who allows an injured athlete to participate when the risk of further damage is high.[4] Unfortunately, because every patient is unique, establishing an unequivocal RTP decision is complicated. In fact, team physicians, athletic trainers, and physical therapists should consider many factors as they collaborate to determine the most appropriate RTP guidelines for a patient.

The majority of RTP research[1–9] to date has focused on assisting clinicians through the process using generic guidelines that can be applied to any sport-related injury or illness. These authors advised that patients should be withheld from full sport participation until the following criteria were satisfied: (1) sport-specific function to the injured tissue was restored, (2) the patient demonstrated sufficient cardiopulmonary function, (3) the patient displayed psychological readiness and was not fearful of reinjury, (4) the injured tissue could be protected using equipment modifications, bracing, or both without putting other athletes at risk, (5) the risk of developing chronic conditions related to the initial trauma was minimal, and (6) the athlete posed no threat to himself or herself or other sport participants. The first criterion, identifying when an injured extremity has regained full sport-specific function, can be particularly challenging to assess in a controlled clinical environment.[9] Baseline functional testing provides an ideal framework for evaluating postinjury physical function, as clinicians can compare the current functional capacity of the affected limb using patient-specific, preinjury data. However, limited time and personnel often prevent the acquisition of such data for every athlete. In such cases, clinicians may consider implementing functional performance tests (FPTs) to assess physical function in the final stages of lower extremity injury rehabilitation.[10–19]

For FPTs, the patient often performs short bouts of single-legged hopping that mimic the dynamic movements commonly performed during athletic participation. This allows clinicians to evaluate muscular strength, endurance, neuromuscular coordination, and joint stability in a controlled clinical environment.[20,21] Investigators[22] have reported normative data for healthy athletes completing common FPTs. The data are helpful in assessing how the performance of a patient's involved limb compares with that of a healthy athlete matched for age and sex. Yet injury or surgery to 1 limb may cause the functional ability of the uninvolved limb to decline over the rehabilitation course, resulting in lingering functional asymmetries.[23–25] Therefore, researchers[22,26] recommended that clinicians also compare FPT outcomes bilaterally by calculating limb symmetry indexes (LSIs) and expressing side-to-side leg differences as symmetric or asymmetric. The LSI can range from 0% to 100%, with 100% representing full functional symmetry between limbs. An LSI of 80% appears to be a common benchmark for patients recovering from an ankle sprain or anterior cruciate ligament (ACL) injury; it indicates that the patient's injured limb must perform at 80% of the healthy uninjured limb before he or she should be cleared for full participation.[27,28] However, in other ACL literature, authors advised LSI benchmarks of 85%,[17,29] 90%,[26,30] or even as high as 95%.[15]

Hence, the exact target LSI clinicians should consider after rehabilitation remains unclear, and the debate persists because of the paucity of normative LSI data.[22] The purpose of our study was to examine LSIs in a large sample of healthy, physically active adults completing 6 common FPTs. First, we calculated average LSI values for each FPT to propose a minimum symmetry benchmark for RTP protocols. Because LSI values tend to fluctuate slightly from person to person, clinicians would do well to modify LSI benchmarks for each patient to avoid a premature return to sport (RTS). Thus, our secondary purpose of the study was to perform multiple regression analyses to determine if independent variables could predict the total variance of the LSI distribution. If so, for patients lacking baseline data, clinicians could enter demographic information into the appropriate regression equation to closely predict an individual's healthy LSI and define a personalized symmetry benchmark for the end of rehabilitation.

METHODS

Participants

In total, 275 healthy and physically active participants volunteered for this study. Participants were recruited from Indiana University and consisted of National Collegiate Athletic Association Division I student-athletes, Army Reserve Officer Training Corps (ROTC) cadets, and recreationally active individuals. Volunteers were excluded if they had a history of fracture or surgery to the lower extremity, a lower body injury that caused loss of function in the 6 weeks before data collection, or a neurologic disorder that caused pain and loss of function. All procedures were approved by the university's Institutional Review Board for the Protection of Human Subjects.

Procedures

The majority of participants completed 1 data-collection session. Due to time constraints, the Army ROTC cadets had to complete 2 FPTs during each of 3 data-collection sessions. However, sufficient rest was allowed between trials, so we were not concerned about their results being biased. Before arriving for data collection, each participant completed an electronic consent form and survey using a computer with Internet access. The survey questions covered each participant's basic demographic information (eg, sex, age), current medical condition, and medical history. Two questions assessed the participant's level of physical activity each week. The first question was "Approximately how many minutes per week are you physically active?" Respondents selected 1 of 6 time windows ranging from *0 to 60 minutes/week* and progressing in increments of 60 minutes to *>300 minutes/week*. The second question asked the individual to rate the average intensity of weekly physical activity using a Likert scale from 0 to 10, with zero representing *sedentary*; 5, *moderate intensity*; and 10, *very high intensity*.

To begin each data-collection session, the participant's height, weight, and limb length were measured. Height and weight measurements were used to calculate body mass index (BMI) by dividing the weight in kilograms by the height in centimeters squared and then multiplying the result by 10 000. Each individual completed a 5-minute stationary bike warm-up and additional stretching as needed before performing 6 single-legged hopping tests using both the dominant and nondominant limb: 6-m crossover hop, side hop, figure-8 hop, triple-crossover hop, lateral hop, and medial hop. The dominant limb was identified by asking each person which leg he or she would use to kick a soccer ball. The order of each FPT and the initial limb were randomized for all participants using a random number generator. For each FPT, the examiner demonstrated the procedure and then the individual completed as many practice trials as needed to become comfortable with the task, followed by 3 successful trials for each limb with a 30-second rest period between trials. If any errors were committed during testing, the trial was discarded, and the test was repeated. Common errors for the FPTs included putting the contralateral foot down, touching any designated line on the mat, and failing to execute the proper maneuver. Speed and distance data were captured using an electronic timer (model Speedtrap 2; Brower Timing Systems, Draper, UT) and a standard tape measure (centimeters), respectively. Each FPT was conducted on a 7-m-long vinyl flooring mat.

Speed FPTs

The 6-m crossover hop, side hop, and figure-8 hop FPTs were measured in seconds to assess speed. For the 6-m crossover hop, participants were instructed to hop a distance of 6 m on 1 limb as fast as possible. However, with each hop, the person had to jump diagonally over a 15-cm-wide line and stay within a 30-cm landing zone (Figure, panel A). The 6-m crossover hop displayed good to excellent test-retest reliability, with an intraclass correlation

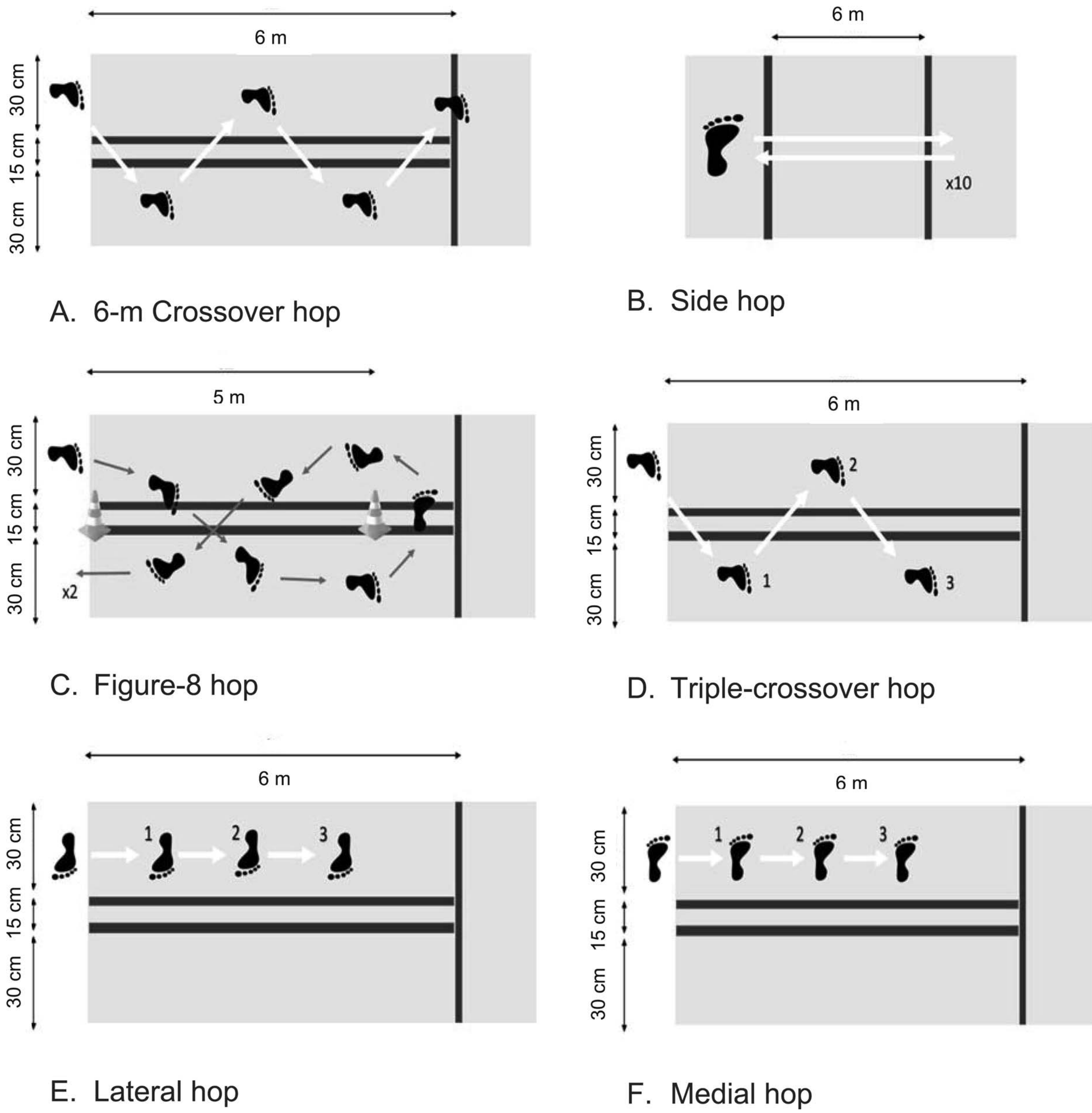

Figure. Functional performance tests. A, 6-m crossover hop. B, Side hop. C, Figure-8 hop. D, Triple-crossover hop. E, Lateral hop. F, Medial hop.

coefficient (ICC) of 0.96.[31] For the side hop, all participants were instructed to complete 10 repetitions by hopping across 2 lines 30 cm apart as fast as possible (Figure, panel B). One repetition consisted of 1 hop back and forth across the 30-cm distance. The side hop had poor to good test-retest reliability, with ICCs ranging from 0.48 to 0.84.[31] For the figure-8 hop, participants completed 2 single-legged hopping laps around 2 cones placed 5 m apart as fast as possible in a figure-8 pattern (Figure, panel C). The figure-8 hop demonstrated good to excellent test-retest reliability, with ICCs ranging from 0.85 to 0.99.[31]

Distance FPTs

The triple-crossover hop, lateral hop, and medial hop were measured in centimeters to assess distance via the side of the test foot that landed farthest away from the start line. For the triple-crossover hop, the participants were instructed to perform 3 alternating hops over a 15-cm-wide line while staying within two 30-cm-wide lanes as far as possible (Figure, panel D). On the third hop, the individuals were instructed to attain balance before placing the opposite foot on the mat for measurement. Hops were consecutive, without pauses. The triple-crossover hop demonstrated good to excellent test-retest reliability, with ICCs ranging from 0.86 to 0.96.[31] For the lateral (Figure, panel E) and medial (Figure, panel F) hop tests for distance, each person was instructed to hop laterally or medially, respectively, 3 times as far as possible. On the third hop, the participants were again instructed to attain balance before placing the opposite foot on the mat for measurement. Oral prompts for the medial and lateral hop tests included making the hops consecutive, avoiding pauses between hops, and keeping the toes of the limb being tested pointed straight ahead. Both lateral and medial hop tests had good

Table 1. Coding Information for Multiple Regressions

Independent Variable	Code	Indication
Sex	0	Male
	1	Female
Weekly physical activity, min	0	60–119
	1	120–179
	2	180–239
	3	240–300
	4	>300

Table 3. Dominant- and Nondominant-Limb Performance for Functional Performance Tests (Mean ± SD)

Functional Performance Test	Dominant Limb	Nondominant Limb
6-m Crossover hop, s	2.6 ± 0.9	2.7 ± 1.0
Side hop, s	8.6 ± 2.4	8.9 ± 2.9
Figure-8 hop, s	10.9 ± 1.9	10.9 ± 2.0
Triple-crossover hop, cm	407.5 ± 107.6	403.2 ± 106.6
Lateral hop, cm	343.4 ± 78.3	339.7 ± 78.9
Medial hop, cm	390.6 ± 85.1	397.2 ± 128.9

to excellent test-retest reliability, with ICCs ranging from 0.87 to 0.95.[31]

Mean Functional Performance

For the 6-m crossover hop, side hop, and figure-8 hop, the mean speed (seconds) of 3 successful trials on each limb was calculated. For the triple-crossover hop, lateral hop, and medial hop, the mean distance (centimeters) of 3 successful trials on each limb was calculated.

Limb Symmetry Index Calculations

An absolute LSI was then calculated for each FPT for each individual.[32] For the speed FPTs, the following equation was used:

$$\mathrm{LSI} = \frac{\text{Fastest Performing Limb mean}}{\text{Slowest Performing Limb mean}} \times 100$$

For the distance FPTs, the following equation was used:

$$\mathrm{LSI} = \frac{\text{Shortest Performing Limb mean}}{\text{Farthest Performing Limb mean}} \times 100$$

Based on these equations, a lower LSI indicates less symmetry between limbs, whereas a value closer to 100 indicates greater symmetry.

Statistical Analysis

We calculated 2 multiple regression models to find variables that may help to predict a person's LSI for each FPT. All prediction models contained the independent variables of sex, BMI, and minutes of physical activity (MPA) per week. One prediction model for each FPT addressed the performance of the dominant limb, while the second prediction model addressed the performance of the nondominant limb. Sex and weekly MPA were both coded as independent variables in the regression models (Table 1). All assumptions were met for the use of multiple regressions. The following assumptions were made: (1) the regression models contained a continuous dependent variable (LSI) and multiple independent variables; (2) residuals were independent as indicated by a Durbin Watson test statistic at or near 2; (3) a linear relationship was present between the dependent and independent variables as verified by visual inspection of partial regression plots; (4) homoscedasticity was evident in an even spread of studentized residuals; (5) no evidence of multicollinearity existed, as tolerance values were >0.1; and (6) the standardized residuals were normally distributed according to histogram plots with superimposed normal curves. Any case with a standardized residual of >3 standard deviations was considered a significant outlier and removed from each FPT regression analysis. No more than 3 outliers were removed from each model.

RESULTS

Performance Outcomes

Demographic information for all participants categorized by weekly MPA is provided in Table 2. All individuals reported weekly physical activity of greater than moderate intensity. The mean performance for each FPT categorized by dominant and nondominant limb is shown in Table 3, while the healthy participants' mean LSI values for each FPT appear in Table 4. The 6-m crossover-hop test produced the lowest mean LSI (91.9 ± 7.2%), while the figure-8 hop test produced the highest value (96.1 ± 3.7%). The mean LSI values for the speed FPTs varied by 4%. However, the values for the distance FPTs were within 1%. The overall LSI for both speed and distance FPTs was 93.8% ± 5.26%.

Multiple Regressions

Speed FPTs. Results of the multiple regressions for all 6 FPTs are given in Table 4 and indicate the variance explained by the overall model (Pearson R) and whether the model can statistically predict LSI values. All 6 speed FPT regression models were statistically significant, showing that sex, BMI, weekly MPA, and the performance of either the dominant or nondominant limb significantly predicted LSI values ($P < .05$). The equations obtained from each regression model and correlations are provided in Table 5. The models for all 3 speed FPTs predicted that the slower a participant was using either limb, the lower the LSI. For example, according to the crossover-hop regression equation, LSI is expected to decrease by 1.4% for every 1-

Table 2. Demographic Information of Participants Grouped by Weekly Physical Activity

Weekly Physical Activity, min	n	Men	Women	Age, y	Height, cm	Weight, kg
120–179	92	46	46	20.26 ± 1.89	171.91 ± 9.62	71.48 ± 15.66
180–239	42	23	19	20.29 ± 2.23	171.69 ± 12.21	69.85 ± 11.61
240–300	34	18	16	20.59 ± 3.51	169.24 ± 8.90	71.05 ± 11.34
>300	107	56	51	19.90 ± 1.83	174.78 ± 9.95	75.24 ± 14.60
Total	275	143	132	20.16 ± 2.19	172.66 ± 10.22	72.64 ± 14.29

Table 4. Limb Symmetry Index Values and Multiple Regression Results for Each Functional Performance Test[a]

Functional Performance Test	Limb Symmetry Index (Mean ± SD)	Multiple Regression Model Using Sex, BMI, Weekly Physical Activity (min), and Dominant-Limb Performance	Nondominant-Limb Performance
6-m Crossover hop	91.9 ± 7.2	$F_{4269} = 2.81$,[b] $P = .026$, Pearson $R = 0.20$	$F_{4269} = 4.98$,[b] $P < .005$, Pearson $R = 0.263$
Side hop	94.1 ± 5.5	$F_{4268} = 11.03$,[b] $P < .001$, Pearson $R = 0.38$	$F_{4267} = 19.02$,[b] $P < .001$, Pearson $R = 0.47$
Figure-8 hop	96.1 ± 3.7	$F_{4268} = 4.33$,[b] $P = .002$, Pearson $R = 0.25$	$F_{4268} = 4.33$,[b] $P < .005$, Pearson $R = 0.30$
Triple-crossover hop	93.4 ± 6.5	$F_{4269} = 1.59$, $P = .176$, Pearson $R = 0.13$	$F_{4269} = 4.19$,[b] $P = .003$, Pearson $R = 0.30$
Lateral hop	93.8 ± 5.2	$F_{4269} = 1.55$, $P = .189$, Pearson $R = 0.15$	$F_{4269} = 4.24$,[b] $P = .002$, Pearson $R = 0.24$
Medial hop	93.8 ± 6.5	$F_{4269} = 3.39$,[b] $P = .010$, Pearson $R = 0.22$	$F_{4269} = 2.77$,[b] $P < .026$, Pearson $R = 0.20$

Abbreviation: BMI, body mass index.

[a] Two multiple regression models were analyzed for each test. Both models contained the independent variables of sex, BMI, and weekly physical activity (min). However, 1 model added mean performance of the dominant limb to the regression, whereas the other model added mean performance of the nondominant limb.

[b] Regression model was statistically significant.

second slower dominant-limb performance. For the side hop, sex was also statistically significant in the model: female participants displayed higher LSIs than male participants. Finally, BMI was statistically significant in the regression model for the figure-8 hop test. A 1-point increase in BMI was associated with a 0.15% decrease in LSI.

Distance FPTs. All multiple regressions for the distance FPTs can be seen in Table 4. For the medial hop, both regression models were statistically significant, indicating that sex, BMI, MPA, and performance using either the dominant or nondominant limb significantly predicted LSI ($P < .05$). For the triple-crossover and lateral hop, only the nondominant-limb regression model was statistically significant ($P < .05$). The equations obtained from each regression model and correlations are given in Table 5. The models for all 3 distance FPTs predicted that the farther a person hops with the dominant or nondominant limb, the higher the LSI. For example, the regression equation for the triple-crossover hop indicated that every 10-cm increase in nondominant-limb jumping distance increased the LSI by 0.2% when all other variables were held constant. For the lateral hop, sex was also statistically significant in the nondominant-limb model: female participants produced a higher LSI than male participants.

DISCUSSION

The first goal of our study was to calculate average LSIs among healthy, physically active adults and use these normative data to propose a minimum RTS benchmark value. Previous researchers[17,27–29] recommended that a postinjury LSI of 80% to 85% permitted a safe return to competition. However, our results indicated that healthy, physically active adults produced average LSI values above 90%. Specifically, the average LSI values for our battery of 6 FPTs ranged from 91% to 96%, which are consistent with a recent report from Lisee et al,[32] who found that average LSIs for adults on the single hop, triple hop, crossover hop, and timed 6-m hop ranged from 94% to 96%. Beyond the FPT literature, authors[33] determined that healthy adults who performed a standing vertical jump demonstrated <10% asymmetry in force production between legs. Similarly, on dynamic-balance tasks, healthy adults displayed 3% to 8% asymmetry in reaching distance when compared bilaterally.[34] Functional performance tests require strength and balance for successful completion. Therefore, our results align well with this research and provide further justification that a 90% LSI is likely the minimum cutoff value between symmetric and asymmetric sport performance.

Our observations also show that healthy, physically active adults may complete unilateral hopping tests with LSIs close to or even at 100%. If clinicians abide by the

Table 5. Regression Equations for Each Functional Performance Test[a]

Functional Performance Test	Multiple Regression Equations Using Sex, BMI, MPA, and Performance Coefficients: Dominant Limb	Nondominant Limb
6-m Crossover hop	LSI = 96.32 + (.28 × Sex) + (.01 × BMI) + (–0.33 × MPA) + (–1.4 × DomPerf[b])	LSI = 97.17 + (0.60 × Sex) + (0.02 × BMI) + (–0.36 × MPA) + (–1.79 × NonDomPerf[b])
Side hop	LSI = 91.67 + (0.70 × Sex[b]) + (–0.06 × BMI) + (–0.19 × MPA) + (0.01 × DomPerf[b])	LSI = 98.68 + (2.11 × Sex[b]) + (0.16 × BMI) + (–0.49 × MPA) + (–0.89 × NonDomPerf[b])
Figure-8 hop	LSI = 103.2 + (0.05 × Sex) + (–0.15 × BMI[b]) + (–0.16 × MPA) + (–0.26 × DomPerf[b])	LSI = 104.05 + (0.41 × Sex) + (–0.13 × BMI[b]) + (–0.19 × MPA) + (–0.39 × NonDomPerf[b])
Triple-crossover hop	LSI = 91.67 + (0.70 × Sex) + (–0.06 × BMI) + (–0.19 × MPA) + (0.01 × DomPerf[b])	LSI = 88.05 + (1.62 × Sex) + (–0.02 × BMI) + (–0.31 × MPA) + (0.02 × NonDomPerf[b])
Lateral hop	LSI = 86.59 + (1.16 × Sex[b]) + (.13 × BMI) + (–0.06 × MPA) + (0.01 × DomPerf[b])	LSI = 83.13 + (2.11 × Sex[b]) + (0.15 × BMI) + (–0.18 × MPA) + (0.02 × NonDomPerf[b])
Medial hop	LSI = 92.64 + (–0.40 × Sex) + (–0.04 × BMI) + (–0.28 × MPA) + (–0.01 × DomPerf[a])	LSI = 93.78 + (–0.69 × Sex) + (–0.05 × BMI) + (–0.23 × MPA) + (0.007 × NonDomPerf)

Abbreviations: BMI, body mass index; DomPerf, mean performance using dominant limb; LSI, limb symmetry index; MPA, minutes of weekly physical activity; NonDomPerf, mean performance using nondominant limb.

[a] Equations contain the unstandardized coefficients for each variable.

[b] The variables in each equation with statistically significant slope coefficients.

Table 6. Target LSIs for 2 Sample Patients Calculated Using Functional Performance Test Regression Equations[a]

Functional Performance Test	Zeke		Zoe	
	Regression Equation	Target LSI, %	Regression Equation	Target LSI, %
6-m Crossover hop	$97.17 + (0.60 \times 0) + (0.02 \times 16.2) + (-0.36 \times 2) + (-1.79 \times 2)$	93.2	$97.17 + (0.60 \times 1) + (0.02 \times 28.8) + (-0.36 \times 2) + (-1.79 \times 5)$	89.2
Side hop	$98.68 + (2.11 \times 0) + (0.16 \times 16.2) + (-0.49 \times 2) + (-0.89 \times 6)$	94.9	$98.68 + (2.11 \times 1) + (.16 \times 28.8) + (-0.49 \times 2) + (-0.89 \times 12)$	93.7
Figure-8 hop	$104.05 + (.41 \times 0) + (-0.13 \times 16.2) + (-0.19 \times 2) + (-0.39 \times 10)$	97.7	$104.05 + (.41 \times 1) + (-0.13 \times 28.8) + (-0.19 \times 2) + (-0.39 \times 18)$	93.3
Triple-crossover hop	$88.05 + (1.62 \times 0) + (-0.02 \times 16.2) + (-0.31 \times 2) + (0.02 \times 500)$	97.1	$88.05 + (1.62 \times 1) + (-0.02 \times 28.8) + (-0.31 \times 2) + (0.02 \times 300)$	94.5
Lateral hop	$83.13 + (2.11 \times 0) + (0.15 \times 16.2) + (-0.18 \times 2) + (.02 \times 400)$	93.2	$83.13 + (2.11 \times 1) + (0.15 \times 28.8) + (-0.18 \times 2) + (0.02 \times 200)$	89.9
Medial hop	$93.78 + (-0.69 \times 0) + (-0.05 \times 16.2) + (-0.23 \times 2) + (0.007 \times 500)$	94.5	$93.78 + (-0.69 \times 1) + (-0.05 \times 28.8) + (-0.23 \times 2) + (0.007 \times 250)$	92.9

Abbreviation: LSI, limb symmetry index.

[a] Refer to Table 1 for the sex and weekly physical activity coding variables. The final value in each equation represents the patient's performance on the test measured in seconds (6-m crossover, side, and figure-8 hop tests) or centimeters (triple-crossover, lateral, and medial hop tests).

90% LSI benchmark at all times, they run the risk of returning some individuals to sport with an 8% to 10% functional bilateral deficit. Although additional work is needed to confirm whether the injury risk is elevated in this scenario, returning an athlete to competition before normal physical function of the injured extremity is restored violates current RTS guidelines set forth by the collaborative efforts of reputable sports medicine associations.[5] Hence, clinicians who regularly use hop tests to compare physical function bilaterally must consider other characteristics (aside from the injury alone) that contribute to a patient's LSIs. Our regression analyses demonstrated that as long as the patient's sex, BMI, and weekly MPA are documented, and the patient can complete the FPT with the uninjured limb using maximal effort, the clinician can predict an LSI that is more representative of healthy, physically active adults with similar demographics. Specifically, our dominant- and nondominant-limb regression models were significant in predicting LSI values for the 6-m crossover hop, figure-8 hop, side hop, and medial hop, with Pearson R values ranging from 0.20 to 0.47. Clinicians can predict a patient's normal LSI for these 4 hop tests regardless of whether the injury is to the dominant or nondominant limb. However, for the triple-crossover and lateral hop, the dominant-limb regression models were not statistically significant. Thus, if a clinician wants to use these 2 hop tests to evaluate limb symmetry in patients with a nondominant-foot injury, we recommend adoption of a cutoff LSI of 93%, as this value represents the mean LSI across our entire participant pool (Table 4).

The following narrative provides a mock scenario demonstrating a clinical application for the statistically significant regression equations presented in this article. Two patients, whom we have named Zeke and Zoe, are both rehabilitating from ankle sprains of their dominant limbs. Zeke and Zoe are both physically active for 180 to 239 minutes each week, but Zeke is a man with a BMI of 16.2 and Zoe is a woman with a BMI of 28.8. As these patients look to RTS, the clinician can first have them complete the battery of FPTs with their uninjured (in this case, nondominant) limb. Then, to establish a target LSI value representative of healthy adults with similar demographics, the clinician enters the patient's information (sex, BMI, and weekly MPA) and the uninjured-limb performance data into the nondominant regression models for all 6 FPTs. The mock patients' individualized target LSI values calculated using the FPT regression equations are shown in Table 6. The predicted LSIs for each FPT vary depending on the patient's personal characteristics. Additionally, the higher LSI predictions for Zeke illustrate how relying on a generic RTP benchmark of 85% to 90% is not suitable for all patients.

Calculating target LSI values using these regression equations may also help clinicians account for the effects of limb dominance on FPT performance. Using normative data, researchers[22] noted that high school and college-aged athletes performed better on some FPTs depending on whether the dominant or nondominant limb was assessed. Therefore, clinicians who evaluate limb symmetry using these tests run the risk of misinterpreting the true functional ability of the injured extremity. A patient's dominant limb may perform 5% better than the nondominant limb under healthy conditions. After a dominant-limb injury, a clinician who is unaware of this difference and abiding by a universal LSI cutoff of 90% may interpret a 10% deficit as within normal limits and clear the patient prematurely. Our regression equations help to prevent this misinterpretation by relying on the slope coefficients associated with each predictor variable. For example, our side-hop regression equations have a negative slope coefficient for the dominant-limb predictor variable and a positive slope coefficient for the nondominant-limb variable. Hence, healthy adults perform the side-hop test slightly better with their dominant limb; the more slowly the patient performs the test using the nondominant limb, the more pronounced the asymmetry. By using these regression equations to adjust LSI benchmarks in this manner, clinicians can better interpret the functional capacity of the injured limb, regardless of whether the injury is on the dominant or nondominant side.

Other variables that significantly predicted LSI values were sex and BMI. To our knowledge, we are the first to evaluate how these independent variables contribute to symmetric performance on hop tests. Previous authors[22,35,36] have reported that men tend to perform better than women on hop tests due to increased power production. However, performing better on certain FPTs may also cause men to appear more asymmetric than women. Our results indicate that sex significantly contributed to the side-hop and lateral-hop prediction models, with women producing higher LSI values (and thus more symmetry) than men. The BMI variable was only significant for the figure-8 hop test. For every 1-point increase in BMI, an individual's LSI decreased by 0.15% for the dominant limb and 0.13% for the nondominant limb. Why an increase in BMI would decrease limb symmetry performance on the figure-8 hop test is unknown. Of all the FPTs implemented in this study, each repetition of the figure-8 hop test took participants the longest to complete (approximately 11 seconds). They seemed to adopt a hopping rhythm and maintained a similar auditory cadence, regardless of which limb they were using. This inadvertent match of hopping rhythm bilaterally may have contributed to the figure-8 hop producing the highest mean LSI value among our FPTs at 96.1% ± 3.7%. Although we are speculating, individuals with higher BMIs may have a more difficult time maintaining a steady hopping cadence from trial to trial, which in turn results in greater variance in limb performance. Regardless, the fact that functional symmetry tends to fluctuate from patient to patient reiterates the importance of finding a method for clinicians to predict more personalized LSIs. Our regression equations provide a novel means of adjusting target LSIs for each patient while simultaneously accounting for specific variables that may cause some patients to perform FPTs with greater asymmetry.

Limitations and Future Research

This study had a number of limitations that warrant further discussion. First, clinicians who intend to use the results in their practice must remember that our participants were healthy, active adults. Therefore, our regression equations help to predict a normal LSI rather than an LSI associated with a reduced risk of reinjury. Future researchers must assess injured populations to determine whether more stringent RTP criteria are needed to reduce reinjury rates. Second, we could not account for all potential LSI predictor variables, so subsequent investigators should consider other factors that may contribute to variation in LSIs among healthy adults. One such variable is sport type. Perhaps athletes who execute plyometric exercises more frequently perform these hopping tests more symmetrically than endurance-type athletes. Finally, we acknowledge the concern of using the uninvolved limb as a sole means of postinjury comparison. Limb symmetry index values may be inflated when measured after ACL reconstructive surgery, likely because the uninvolved limb is no longer subject to the demands of sport participation and loses muscular strength during the lengthy rehabilitation process.[25] As such, the functional capacity of the involved limb may appear greater if the clinician is comparing it to an extremity that does not truly represent a healthy limb. Further evaluation is needed to identify specific injuries or surgeries that reduce hop performance of the uninvolved limb. In the meantime, we recommend that clinicians implement strength training and functional weight-bearing exercises for the uninvolved limb early in the rehabilitation protocol to prevent such deficits.

CONCLUSIONS

Limb symmetry index values on unilateral hopping tests vary among healthy, physically active adults. Relying on universal LSI values to categorize patients' functional performance as normal or asymmetric may result in some patients returning to competition before their functional symmetry has been restored. We recommend that all patients reach a minimum LSI of 90% before they RTS. However, clinicians should use the proposed regression equations to identify patients who represent healthy adults with LSIs well above 90%. As long as the patient can hop on the uninjured limb with maximal effort, the clinician can account for sex, BMI, and MPA per week to create an individualized LSI for each person.

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